A STUDY OF A NEW TYPE OF CONVERTER

by

HELMER SORENSON

A Thesis Submitted for the Degree of

Master of Science

UNIVERSITY OF WISCONSIN

1 9 2 2

TABLE OF CONTENTS.

Table of Symbols.

Unless otherwise specified in the text, the symbols used in this paper will have the following significance.

a = Ratio of Transformation

E = Induced Voltage

E_1 = Primary Induced Voltage of a transformer.

E_2 = Secondary Induced Voltage of a transformer.

f = Frequency.

I = Current.

I_1' = Load Component of Primary Current of a transformer.

I_1 = Primary Current of a transformer.

I_2 = Secondary Current of a transformer.

j = Operating Factor which rotates a vector anti-clockwise thru ninety degrees.

N = Turns.

n = Speed, or Number of Phases.

P = Power

p = Number of poles.

p.f. = Power Factor.

r = Resistance.

r_e = Effective resistance of a transformer.

V = Terminal Voltage.

x = Reactance.

x_e = Effective Reactance of a transformer.

z = Impedance.

z_e = Effective Impedance of a transformer.

Z = Number of Inductors.

η = Efficiency.

θ = Angle of Lag.

τ = Angle of Lag.

Σ = Summation.

φ = Flux.

I. INTRODUCTION AND PURPOSE.

The electric converter is one of the most important pieces of apparatus found in a modern power distribution system. It is the connecting link between the universally used alternating current generators and the direct current utilizing devices. One of its important applications is to supply direct current for running street cars.

A great deal of work has been done upon the synchronous converter; but little investigation has been made upon certain earlier types which preceded it. The type discussed in this paper, designated thru-out the discussion by the title of "Static Converter", has been neglected so long that the author thought himself the original inventor. Hope was also entertained of converting at higher efficiency than with the modern synchronous converter.

The purpose of this paper is:

(a) To give a historical sketch of these early types of converters.

(b) To give the theory of the new type of converter.

(c) To present the experimental checks of the theory advanced.

The author is indebted to Prof. J.R. Price for his many valuable suggestions and interest in the work. Indebtness is also acknowledged to Mr. L.J. Peters for help in taking oscillograms and to Mr. D.H. McConnell for aid in securing data during the more complicated test runs.

II. HISTORICAL REVIEW.

(1) Early work.

Before taking up the research work, it has been thought well to give a brief account of the development of the methods used to convert electrical energy from one form into another, and to make statements which will later be used as a basis for comparison of the performance of the various types of machines. For a fuller account of these earlier types the reader is referred to the appended list of references.

(a) The Rectifier Type.

This type is the oldest, dating back to 1838 according to Thompson#, and in 1869 they were used for the field magnets of self-exciting alternators. This apparatus consists simply of a synchronously revolved commutator whereby the alternations in the current are rendered unidirectional or whereby a direct current is chopped up into negative and positive loops. This device is a crude sort of makeshift as no true direct current is produced, especially from single-phase alternating current, or on the other hand no true alternating current is produced by reversing the poles of a continuous current circuit. The main defect of this class of devices is excessive sparking. The main advantages are simplicity and freedom from coils of any kind. This type of converter is used today in the cement making industry for dust precipitation by the Cottrel method. The efficiency does not exceed 55% in most cases.

#Thompson, S.P. -- Dynamo Electric Machinery, Fourth Edition, Page 652.

(b) The Inductorium Type.

According to Colles#, this type is "characterized by a series of induction coils, which may or may not be stationary, arranged in a circle and having their primary and secondary coils, one or both, connected to the respective segments of a commutator: the apparatus is not, in general, self-rotative or self-regulating, ... but must be rotated by a donkey-motor or other external source of power. One or two commutators are used, according as a direct and alternating or two direct currents are wanted. In this class there are three well-marked subclasses:

1. The stationary independent coil type, in which each induction coil is wound upon a separate core, and separately connected to the commutator or commutators thru slip-rings....

2. The stationary ring type, in which the separate induction coils are now wound together all upon one ring, which has two independent sets of coils wound thereon Gramme fashion, and connected to the commutator or commutators thru slip-rings.

3. The rotating ring type, identical with the former, except that to avoid the slip-ring connection and possibly to give stability to the rotation, the induction ring is mounted on the commutator-shaft. The "dynamotor" has not been reached, as no external fields are provided."

#Colles, G.W. -- Rotary Transformers.-- The Journal of the Franklin Institute, 1901. Page 212.

The fatal defect of these devices is the excessive sparking. The output from such a piece of apparatus is also necessarily very limited and the efficiency of conversion is low.

2. Rectifiers.

Brief mention is made here of the later development of the mercury-vapor, and the electrolytic rectifiers. These methods of converting electrical energy are, however, distinct from the methods considered in this paper, depending upon the electrical valve action of chemicals. Mercury-vapor rectifiers are being developed for heavy power service and they may supplement the synchronous converter for supplying direct current for railway systems. Electrolytic rectifiers seldom exceed 60% efficiency; the mercury-vapor rectifier runs higher, going up to about 80%.

3. Motor Generators.

Motor generators are too well known to require much description. They usually consist of an alternating current motor, of either the synchronous or induction type, coupled directly to a direct-current generator. The chief advantage of motor-generators is that their alternating current and direct current sides are entirely independent.

The efficiency of a 25-cycle motor generator will be from six to eight per cent less than the efficiency of a corresponding rotary converter with its necessary accessaries.

In the case of 60-cycle apparatus the difference is from three to six percent. The copper losses do not increase so rapidly with decreasing power factor as do the copper losses in a rotary converter. Rotary converters cost from 25 to 30% less than the corresponding motor -generators.

4. Synchronous Converters.

The synchronous converter is usually employed whereever large amounts of power must be converted. Its general theory and design is so intimately related to the static converter that a brief summary will be given.

In any direct-current generator the induced voltages are alternating, the current being rectified by means of the commutator. Alternating current can therefore be taken from any direct-current generator by bring out taps from the armature at suitable points and connecting them to slip rings.

A machine tapped in this way will operate either as a direct-current motor or generator, or as an alternating-current synchronous motor or generator. It may therefore be used to convert alternating into direct-current, or to convert direct into alternating current.

The voltage ratio of an n-phase converter is found as follows:

The electromotive force induced in any inductor is

$$e = E_m \cos \Delta$$ where E_m is the maximum electromotive force induced in a single conductor and

Δ is the position angle of the inductor with reference to the resultant field. The direct-current voltage will be

$$E_{dc} = \sum_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} E_m \cos\Delta$$

$$= \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} E_m \frac{Z}{\pi} \cos\Delta \, d\Delta$$

$$= 2 \frac{Z}{\pi} E_m \qquad (1)$$

Where Z is the number of inductors in series between brushes.

If there are n slip-rings, the angle between any two taps for any phase will be $2 \frac{\pi}{n}$ electrical radians. If there are more than two poles, n is the number of taps per pair of poles.

The maximum alternating current voltage between these two taps will be

$$E_{dc} = \int_{-\frac{1}{2}\left(\frac{2\pi}{n}\right)}^{+\frac{1}{2}\left(\frac{2\pi}{n}\right)} E_m \frac{Z}{\pi} \cos\Delta \, d\Delta$$

$$= 2 E_m \frac{Z}{\pi} \sin \frac{\pi}{n} \qquad (2)$$

If a sine wave of e.m.f. is assumed, the effective or r.m.s. alternating current voltage will be

$$E_{ac} = \frac{2 E_m \frac{Z}{\pi} \sin \frac{\pi}{n}}{\sqrt{2}} \qquad (3)$$

The ratio of the voltages on the two sides will be

$$\frac{E_{ac}}{E_{dc}} = \frac{\dfrac{2\, E_m \dfrac{Z}{\pi} \sin \dfrac{\pi}{n}}{\sqrt{2}}}{2 \dfrac{Z}{\pi} \quad E_m}$$

$$= \frac{1}{\sqrt{2}} \sin \frac{\pi}{n} \qquad (4)$$

The actual voltage ratio of converters will differ slightly from this, being influenced by the flux distribution in the air gap.

Current relations:

Since the input times the efficiency must be equal to the output the following relation must be true:

$$\frac{p}{2} \text{ (p.f.) } (\eta) \; n \, V_{ac} \, I'_{ac} = V_{dc} \quad I_{dc}$$

Where I'_{ac} is the coil alternating current. And

$$\frac{\frac{p}{2} I'_{ac}}{I_{dc}} = \frac{1}{n \text{ (p.f.) } (\eta)} \frac{V_{dc}}{V_{ac}} \qquad (5)$$

Now in general the total line current is equal to the coil current multiplied by 2 sin $\frac{\pi}{n}$ and by the number of pairs of poles. Hence, replacing the coil current in equation (5) by the total line current, I_{ac}, gives

$$\frac{I_{ac}}{I_{dc}} = 2 \sin \frac{\pi}{n} \frac{1}{n \text{ (p.f.) } (\eta)} \frac{V_{dc}}{V_{ac}}$$

Since $\frac{V_{dc}}{V_{ac}}$ is very nearly equal to $\frac{E_{dc}}{E_{ac}}$, we may write as an approximation:

$$\frac{I_{ac}}{I_{dc}} = 2 \sin\left(\frac{\pi}{n}\right) \frac{1}{n\ (p.f.)\ (\pi)} \frac{1}{\frac{1}{\sqrt{2}} \sin \frac{\pi}{n}}$$

$$= \frac{2\sqrt{2}}{n\ (p.f.)\ (\pi)} \qquad (6)$$

We turn now to a consideration of the static converter, and the application of the above equations to this machine.

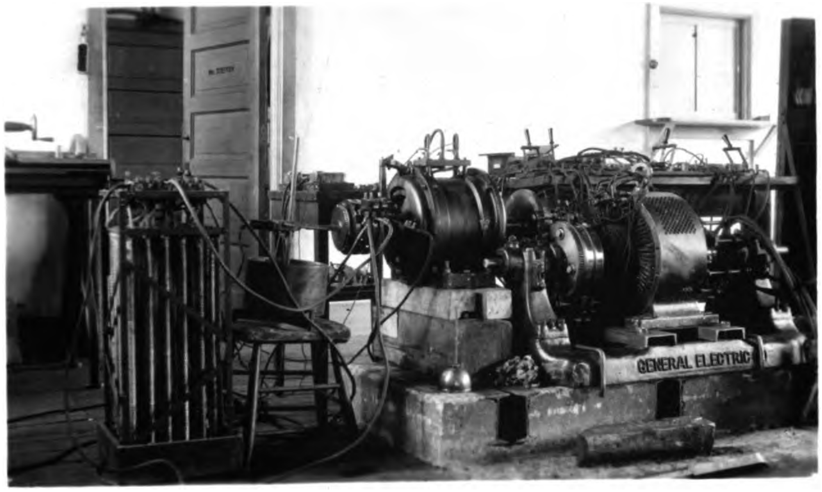
III. THEORY OF THE STATIC CONVERTER.

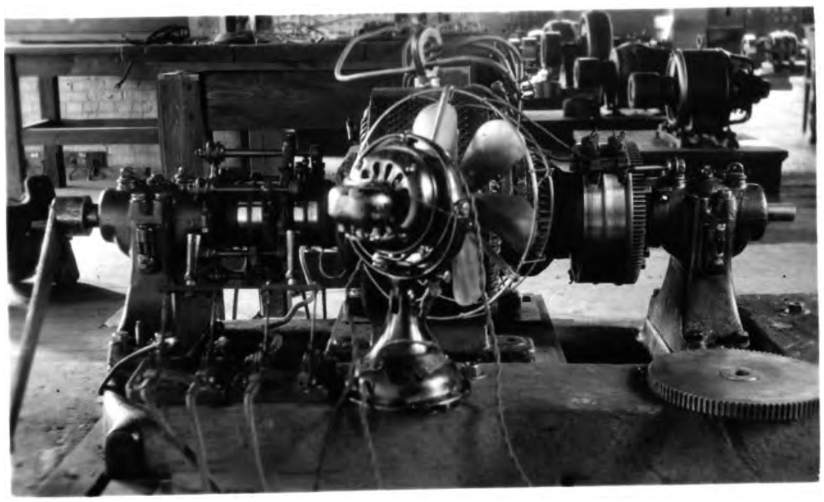
1. General Description.

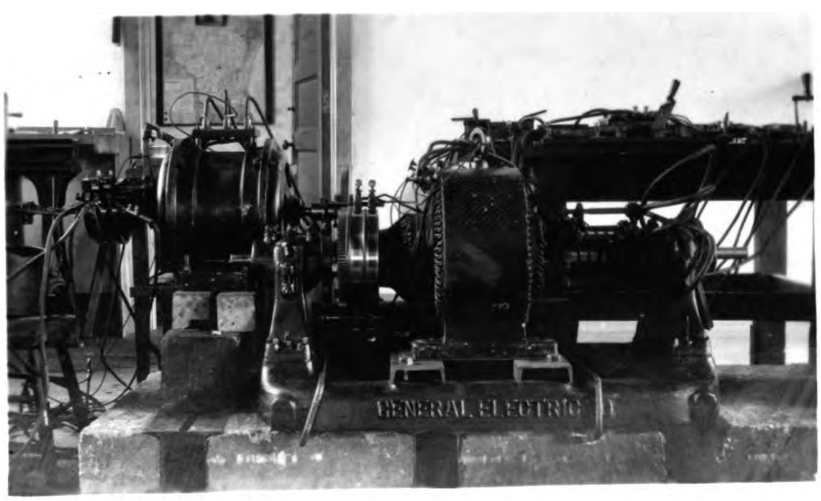
The static converter consists of a stationary polyphase stator or primary, a stationary armature or secondary, and a synchronously driven set of rotating brushes. In the experimental machine, an old four-pole, Gramme ring wound, three-phase stator of an induction motor was used as the primary. The secondary consisted of the armature from a General Electric type H.C. converter. The revolving brush mechanism was designed by the author and built in the university shops. The accompanying photographs show the assembly on the test floor.

Power was applied to the stator producing the revolving magnetic field. This in sweeping over the inductors on the stationary armature, induced voltages just as in the case where the armature revolved in a stationary field flux. The revolving brushes were adjusted until a maximum difference of potential was secured.

Alternating-current power was also supplied directly to the slip rings of the armature in some of the runs; and tests were also made with the machine acting as an inverted converter, direct-current power being applied and alternating-current power being taken out. These various conditions will now be studied.


GENERAL ELECTRIC




GENERAL ELECTRIC

2. Calculations.

The data on the apparatus used in the laboratory is as given below:

Converter E.E.#1032. H.C.-4-7½-1800-110V#88355. G.E.

Armature:

Type of winding	Multiple drum.
No. of circuits	4
Conductor	.102
Insulation	DCC
No. of single coils	96
Turns per coil	3
No. of slots	48
Conductors per slot	12
Number of commutator segments	96
Connection diagram	R.F.C.406

Main shunt field:

Conductor	.049
Insulation	DCC
No. in multiple	1
Turns in series per coil	1749
Mean length turn	1.97 ft.
Calc. resist. at 25 degrees C.	15.3 ohms.

Dimensions:

Length of bearing surface	14 inches.
Diameter of armature	9 inches.
Area of one pole shoe	25 sq. in.

Induction Motor E.E.#1033.-Allgmeine Elektricilats Gesellschaft, Berlin, Germany. #3784.

100 volts, DR - 50, 3-phase.

Stator

No. of slots	72
Conductors per slot	3
Type of winding	Gramme ring.
Conductor size	3.50 millimeters -- .138 inches.
Resistance per phase	.078 ohms.
Mean length turn on stator	22.5 inches.

Short-circuit test of Static Converter.

At 25 cycles:

V_{12}	V_{23}	I_1	I_2	P_t	Per Phase: r_e	z_e	x_e
24.3	24.4	49.3	49.4	1.608	.219	.284	
22.2	22.3	42.2	42.7	1.24	.229	.303	
14.1	14.17	21.8	22.0	..396	.275	.302	
26.4		46.4		.96	.223	.284	
				Mean =	.22	.30	.202

At 60 cycles:

33.6	33.6	43.9	44.6	1.534	.261	.438	
29.2	29.1	34.7	35.0	1.016	.278	.482	
24.5	24.6	25.5	25.5	.592	.304	.555	
25.2			21.7	.296	.304	.580	
				Mean =	.28	.50	.414

Measured ratio of transformation = 1.466

Several method of computing the direct-current voltage and current will now be shown.

Equation (4) previously developed for the synchronous converter will apply to the static converter provided we divide the voltage impressed on the stator by the ratio of transformation to get the voltage applied to the armature. E_{ac} becomes the terminal (line) voltage because the brushes are adjusted to get the maximum difference in potential existing in the coils. The direct-current voltage is then

$$E_{dc} = \frac{E_{ac}\sqrt{2}}{a \sin \frac{\pi}{n}} \qquad (1)$$

Because of the high reactance of the machine, a low power factor may be expected. Assuming a power factor of 80% and a full load primary current of 25 amperes (See Fig.1)

$$\dot{E}_{ac} = V - I(\cos\theta - j\sin\theta)(r_e + j\,x_e) \qquad (2)$$

$$= \frac{110}{\sqrt{3}} - 25\ (.8 - j.6)(.28 + j.414)$$

$$= 51.7 - j\ 4.08$$

$$E_{ac} = 51.9 \text{ volts.}$$

And

$$E_{dc} = \frac{51.9\sqrt{2}\sqrt{3}}{1.466 \sin \frac{\pi}{3}}$$

$$= 100 \text{ volts.}$$

Similarly, the current is calculated from

$$I_{dc} = \frac{n\,(p.f.)\,(\eta)\,a\,I_{ac}}{2\sqrt{2}} \qquad (3)$$

At an assumed efficiency of conversion of 80% and a power factor of 80%, the direct-current would be

$$I_{dc} = \frac{3\,(.80)\,(.80)\,1.466 \times 25}{2\sqrt{2}}$$

$$= 25 \text{ amperes.}$$

At 25 cycles a lower impressed voltage must be used. Using an impressed voltage of 80 and a current of 50 amperes, the corresponding direct-current values are

$$E_{dc} = 60.6 \text{ volts.}$$

$$I_{dc} = 50 \text{ amperes.}$$

As a check upon the foregoing calculations, the direct-current voltage may also be found by the ratio of the fluxes cutting the armature inductors (1st) when in the synchronous converter field (2nd) when in the 3-phase stator field. Now the flux existing in the first case is given by the familiar direct-current equation

$$E_{dc} = \frac{p}{a}\,\frac{\Phi\,Z\,n}{60 \times 10^{8}} \qquad (4)$$

Substituting the value of the constants from the data on the synchronous converter

$$110 = \frac{4}{4} \frac{\phi 576 \times 180}{60 \times 10^8}$$

And

$$\phi = 637{,}000 \text{ lines per pole.}$$

The induced voltage in a synchronous generator is#

$$E = 4.44 \, N \, f \, \phi_m \, 10^{-8} \qquad (5)$$

For the three-phase stator used in the test

$$\frac{110}{\sqrt{3}} = 4.44 \times 72 \times 60 \times \phi_m \, 10^{-8}$$

And

$$\phi_m = \frac{110 \times 10^{-8}}{4.44 \times 72 \times 60 \times \sqrt{3}} = 330{,}000 \text{ lines.}$$

The other two phases also contribute to the resultant flux, thus

$$\phi = 330{,}000 \, \frac{3}{2}$$

$$= 495{,}000 \text{ lines per pole.}$$

The voltages induced are directly proportional to the fluxes, hence

$$E_{dc} = 110 \, \frac{495{,}000}{637{,}000}$$

$$= 85.5 \text{ volts.}$$

#Lawrence, R.R. - Principles of Alternating Current Machinery - N.Y. 1916. Page 21.

Knowing the ratio of transformation between the stator and the armature of the static converter, the current and voltage may be computed by a third method from the simple transformer relations:

$$\frac{I_1'}{I_2} = \frac{N_2}{N_1} = \frac{1}{a} \qquad (6)$$

Where I_1' is the load component of the stator current.

And

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = a \qquad (7)$$

The rotating brushes will be adjusted to get a maximum difference in potential. This corresponds to picking off the peak value of the induced alternating-current voltage. The corresponding value of the current depends upon its angle of lag or lead with relation to the voltage and may be any value from zero to its peak value. Since the static converter has an effective resistance of r_e ohms, and an impedance of z_e ohms, the current will lag by approximately

$$\cos^{-1} \frac{r_e}{z_e} = \tau \qquad (8)$$

The actual angle of lag depends upon the effect of the load current. In computing the actual angle of lag for a given load, resource must be made to the vector diagram. Let τ represent the angle of lag of the secondary current behind the secondary voltage.

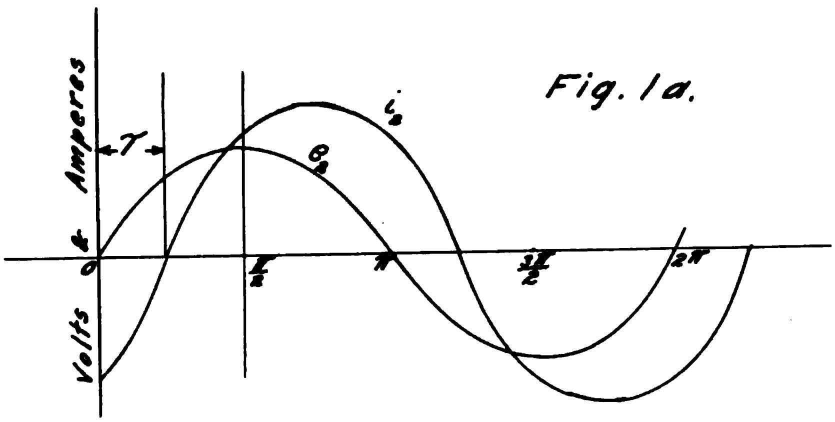


Fig. 1a.

If the peak value of the alternating-current wave is I_p amperes, then the direct current would be

$$I_{dc} = I_p \sin (90 - \tau) \tag{9}$$

Or

$$I_{dc} = \sqrt{2} \quad I_2 \quad \cos \tau \tag{10}$$

The direct-current voltage will be

$$E_{dc} = \sqrt{2} \quad E_2 = \frac{\sqrt{2} \quad E_1}{a} \tag{11}$$

Figure 1a is a sketch of the current and voltage relations at time of commutation. By using the measured ratio of transformation, a, between terminals, there is no necessity of finding out whether the windings are connected in star or mesh.

As an Inverted Converter.

If the brushes are revolved by a synchronous motor, and direct-current voltage is impressed, alternating-current power may bd taken off the primary. Its frequency depends upon the speed of the rotating brushes.

The alternating-current voltage and current may be found by equations (10) and (11). For the inverted converter these equations assumethe form

$$E_{ac} = \frac{a \ E_{dc}}{\sqrt{2}} \qquad (12)$$

$$I_{ac} = \frac{I_{dc}}{a \sqrt{2} \ \cos} \qquad (13)$$

If the winding of the secondary is mesh connected, the current in equation (13) must be multiplied by $\sqrt{3}$ to get the terminal or line current.

Application of the Theory.

For the 60 cycle conditions.

$\cos \tau = .35$ From the data on Fig.7.

Then

$$I_{dc} = 1.64 \frac{25.4}{\sqrt{3}} \sqrt{2} \times .35$$

$$= 11.9 \text{ amperes.}$$

The voltage will be

$$E_{dc} = \frac{\sqrt{2} \times 110}{1.64}$$

$$= 94.8 \text{ volts.}$$

Power input

$$= \sqrt{3}\ V\ I_1\ \cos 0$$

$$= \sqrt{3} \times 110 \times 25 \times .35$$

$$= 1.67 \text{ Kw.}$$

Power output

$$= E_{dc}\ I_{dc}$$

$$= 94.8 \times 11.9$$

$$= 1.13 \text{ Kw.}$$

Efficiency of conversion

$$= \frac{1.13}{1.67} = 67.7\ \%$$

IV. CHECK OF THE THEORY.

I. Design of the Revolving Brushes.

As originally planned, the tests were to be carried out with 60 cycle alternating current. The brush mechanism was therefore designed for a synchronous speed of 1800 r.p.m. After the machine was set up for test, results were found to be erratic and trouble was continually experienced due to poor commutation , until fin ally all tests were carried out at 25 cycles.

Plate 1. illustrates the design which was finially adopted as satisfactory. The brass slip rings have an outside diameter of ten inches., giving the enormous peripheral velocity of

$$v = \pi dn$$

$$= \frac{\pi\, 10 \times 1800}{12}$$

$$= 4710 \text{ ft./ min.}$$

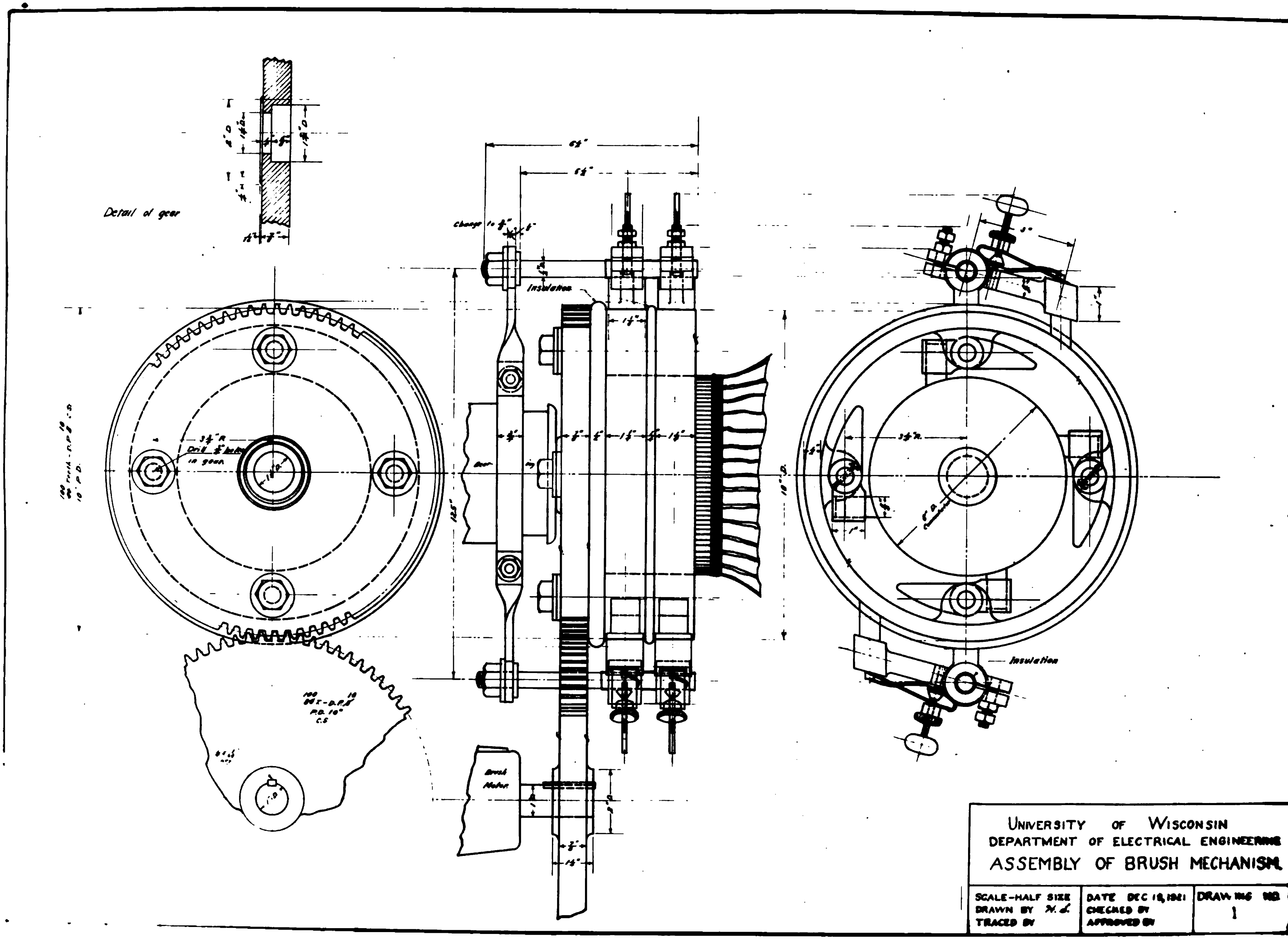
The thickness of the slip rings was calculated by Love's formula for the tangential true unit stress#

$$S = \frac{w\,\omega^2(1+\lambda)(1-2\lambda)}{8g(1-\lambda)}\left[(3-2\lambda)(r_1^2+r_2^2)+\frac{3-2\lambda}{1-2\lambda}\,\frac{r_1^2 r_2^2}{x^2}-x^2\right]$$

The stress set up in the slip ring was checked by the formula

$$S = \frac{w\,v^2}{12\,g}$$

Merriman, M. -- Mechanics of Materials -- 11th edition, N.Y. 1916. page 428.


UNIVERSITY OF WISCONSIN
DEPARTMENT OF ELECTRICAL ENGINEERING
ASSEMBLY OF BRUSH MECHANISM
SCALE-HALF SIZE
DRAWN BY H. L.
TRACED BY
DATE DEC 18, 1921
CHECKED BY
APPROVED BY
DRAWING NO.
1
Detail of gear
Insulation
Brush Motor
100 Teeth - D.P. 10
10" P.D.
Drill 3/8" holes
Change to

In the equations on the previous page, the letters have the following significance

w - weight per cubic inch = .30 lbs. for brass

ω - angular velocity in radians /sec.

λ - factor of lateral contraction = $\frac{1}{4}$

r_1 , r_2 - radii in inches

x - radius to any point.

The minimum diameter of the gears was fixed by the size of the slip rings to a value of 10 inches, thus giving a speed of 4710 ft./min. of the pitch circle. The only objection I could find to this speed was the noise. The bursting speed of a disc in r.p.m. is#

$$N = \frac{180}{\pi} \sqrt{\frac{S\ g}{(R^2 + Rr + r^2)\ w}}$$

$= 24400$ r.p.m. This gave a factor of safety of 13.55 at 1800 r.p.m.

The brushes were designed to carry 40 amperes safely.

The brush holders gave considerable trouble in design because an attempt was made to utilize the enormous centrifugal force to get firm contact of the brushes on the commutator. This meant a nice adjustment of counter-weighting which did not work out well in practise. Springs were found necessary to give the correct pressure at all times. Four brush holders, for the stationary brushes, were adapted from the G.E. synchronous converter to collect the direct current from the slip rings.

#Machinery's Handbook - Industrial Press, N.Y. 1919, 5th Ed.

2. Experiments.

a.) General Description of Tests.

Figure 3. is a ddiagram of the connections used for most of the tests. The field rheostats R_2, R_3, were placed near the static converter so as to be convenient for varying the frequency and impressed voltage. Al. represents a 3-phase, 25 or 60 cycle alternator. For the 60-cycle runs, power was also taken directly from the switch-board.

The brush motor was a small G.E.. Type SKS-4-½ Form C synchronous motor. This motor proved inadequate to drive the brushes, and a large (5 H.P.) Swiss motor was the only other 4-pole machine available. This motor was of the induction type with a wound rotor. It was changed into a synchronous motor by introducing direct current into the rotor R, as shown in Fig. 2. Figure 2, illustrates how a brake test of this motor was made before using it to drive the brushes of the static converter in order that some data might be available on its operating characteristics. In Fig. 3 F_1 represents this wound rotor and R_1 is a lamp-bank in series for controlling the current input. This motor developed over 4 H.P. when thus modified, and no further trouble was experienced in getting synchronous speed for the brushes.

The frame and the armature from the synchronous converter were used to build up the static converter. The banding-wires had to be removed from the armature in order to get it into the stator opening. The air-gap was therefore very

small -- on the order of a sixteenth of an inch. In the 60-cycle runs considerable heating of the gear bearing took place; a fan was therefore installed to blow cold air on the brush mechanism for these tests.

When starting up, the brush motor was first brought up to synchronous speed. Then power was applied to the stator S (primary) of the converter, and lastly, the direct-current load was placed on the machine. The load consisted of lamp-banks in parallel for all runs. The power input was measured at the polyphase board.

Figure 4 illustrates how the test was made with the converter doubly-fed. The incoming three-phase power was split up, part going to the stator S (primary) and part going to the slip rings on the alternating-current side of the armature (secondary). The voltage was controlled by a three-phase potential regulator and was stepped down by the transformers T. P_1 and P_2 represent polyphase measuring boards. It should be noted that the total power input was measured at P_1, and the power input to the armature was measured at P_2. The difference between P_1 and P_2 is therefore the power going to the stator. The transformer losses are therefore included in the power measured at P_2. This was desired, since transformers would always be a necessary evil whenever the static converter would be doubly-fed.

When operated inverted, no attempt was made to take power from the armature slip-rings; all load was taken from the stator.

b.) Data. Test of the Static Converter.

Frequency of......................60 cycles/sec.

Alternating-current voltage......110 volts.

D.C. Output.			A.C. Input to Stator			%	%
Volts	Amps.	Kw.	Amps.	Kw.	Kva.	p.f.	Eff.
100	0	0	22.3	.60	4.25	14.1	0
98	.8	.0784	22.9	.70	4.36	16.1	11.2
96	2.9	.288	25.5	1.00	4.86	20.6	27.7
96	3.9	.374	22.9	1.08	4.37	24.8	34.7
95	4.8	.416	23.7	1.20	4.60	26.1	38.0
94	5.7	.536	23.7	1.32	4.62	28.6	40.6
93	7.6	.707	23.7	1.40	4.60	30.4	50.5
90	11.0	.990	25.4	1.70	4.84	35.1	58.3

Slight sparking occurred towards the last of the run.

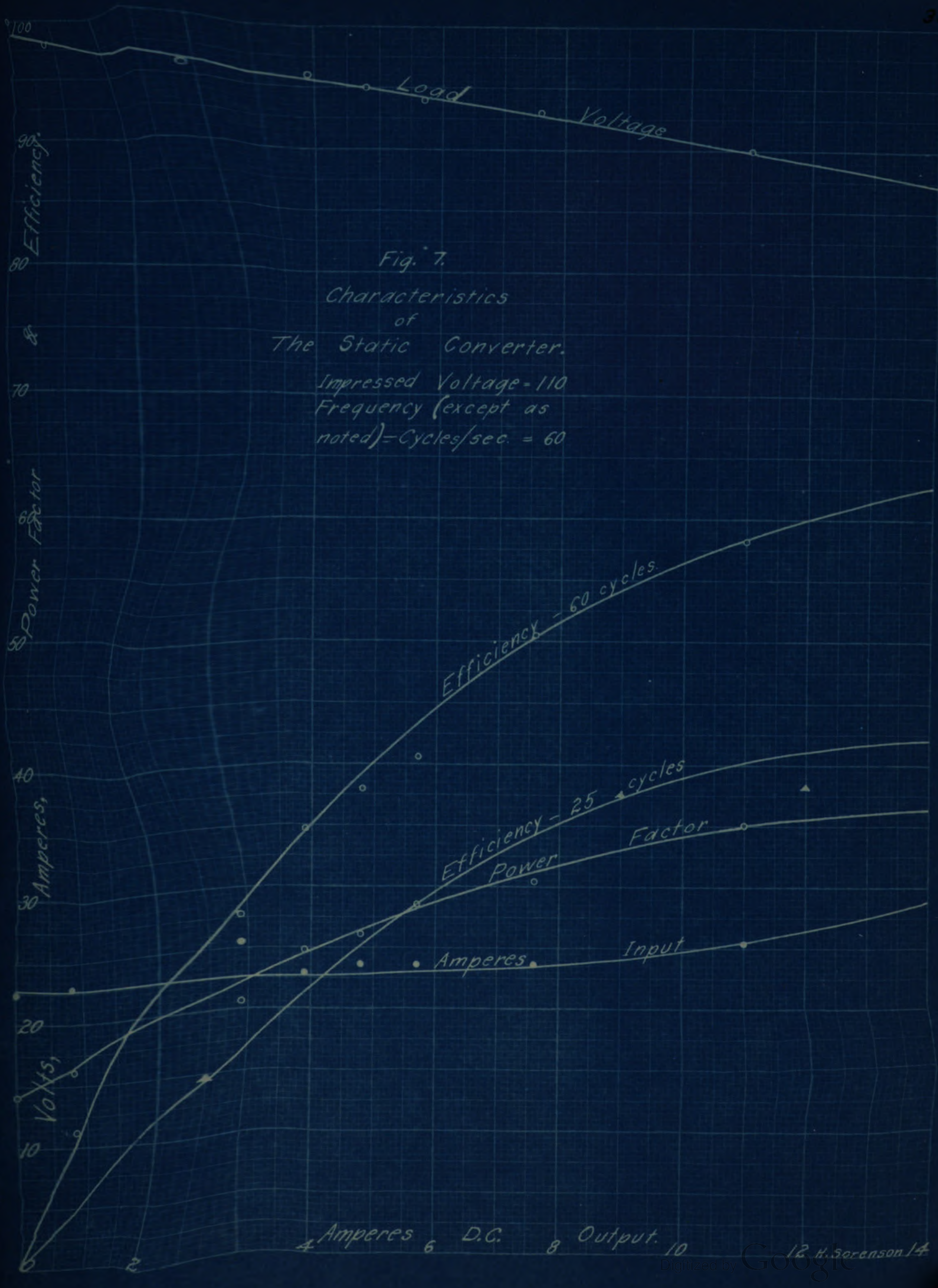


Fig. 7.
Characteristics of The Static Converter.
Impressed Voltage - 110
Frequency (except as noted) - Cycles/sec. = 60

Test of a Polyphase Synchronous Converter. -- Jan.17,'21

General data:

Converter #1032, G.E. 7½ kw. D.C. output 68 amperes, 110 volts. Frequency 60 cycles/sec.

Field current .85 amperes.

Transformer primary 3-phase voltage 130.

D.C. Output.			A.C. Input to Stator			%	%
Volts	Amps.	Kw.	Amps.	Kw.	Kva.	p.f.	Eff.
99.0	88.0	8.72	46.0	10.25	10.40	98.7	84.4
99.0	70.0	6.93	40.0	8.50	9.00	94.4	80.8
100.0	57.0	5.70	33.5	7.00	7.55	92.7	80.3
102.0	43.5	4.44	27.0	5.75	6.08	94.5	76.1
104.0	31.0	3.23	22.0	4,50	4.95	91.0	70.4
105.0	21.0	2.21	18.0	3.45	4.05	85.2	62.4
106.5	13.0	1.39	15.0	2.55	3.38	75.4	52.5
107.5	6.0	.65	12.0	1.75	2.70	64.8	35.1
109.5	0	0	10.0	1.25	2.25	55.6	0

Run #2. Characteristics of the Static Converter.

Frequency of supply............... 25 cycles/sec.

Alternating-current voltage ...... 80 volts.

D.C. Output.			A.C. Input to Stator			%	%
Volts	Amps.	Kw.	Amps.	Kw.	Kva.	p.f.	Eff.
74.0	0	0	43.3	1.08	6.00	18.0	0
74.0	2.5	.185	43.5	1.26	6.03	20.9	14.7
75.0	9.0	.665	44.3	1.77	6.15	28.8	37.6
74.0	12.0	.884	44.4	2.34	6.16	38.0	38.0
70.0	16.5	1.155	45.9	2.78	6.36	43.8	41.6
65.0	22.5	1.463	46.4	3.16	6.43	49.2	46.3
63.5	28.0	1.778	47.7	3.46	6.61	52.2	51.4
63.0	32.0	2.016	48.7	3.92	6.75	58.1	51.4
62.0	37.5	2.325	49.1	4.30	6.81	63.2	54.1
60.0	43.0	2.580	50.2	4.64	6.95	66.8	55.6
58.0	47.5	2.755	52.3	5.02	7.25	69.3	55.0
56.0	53.0	2.968	51.8	5.00	7.18	69.7	59.3
55.0	57.5	3.163	53.3	5.34	7.39	72.3	59.2
53.0	63.0	3.338	54.5	5.64	7.55	74.7	59.2
52.0	72.0	3.744	60.3	6.62	8.36	79.2	56.6

Absolutely no sparking even when commutating 72 amperes.

Run #3. Effect of varying the Frequency .

A.C .Voltage constant at 80 volts.

D.C. Load constant at 20 amperes.

D.C. Output		A.C. Input to Stator.				%	%
Volts	Kw.	Amps.	Kw.	Kva.	f.	p.f.	Eff.
69.5	1.41	46.8	2.60	6.61	22.0	39.4	54.2
69.0	1.37	42.8	2.46	5.93	23.3	41.4	55.7
68.0	1.33	40.9	2.38	5.66	25.1	42.1	55.9
69.8	1.41	35.5	2.30	4.92	26.7	46.8	61.3
69.4	1.39	32.7	2.18	4.53	28.3	48.2	63.8
69.0	1.40	32.0	2.18	4.43	30.0	49.3	64.2
69.0	1.38	30.4	2.10	4.22	31.7	49.8	65.7
68.0	1.35	30.2	2.06	4.18	33.3	49.3	65.3
66.5	1.28	28.6	1.94	3.77	35.0	48.9	66.0

Run #4. Doubly-fed Static Converter.

Impressed Voltage ..... 80 volts.

Impressed Frequency.... 25 cycles/sec.

D.C. Output.			Armature			Total Input.	
Volts	Amps.	Kw.	Volts	Amps.	Kw.	Amps.	Kw.
77.0	0	0	80.0	4.7	.60	56.3	1.47
75.5	5.0	.378	80.0	4.5	.59	58.3	1.84
72.5	12.0	.870	80.0	8.4	1.10	64.2	2.50
71.8	18.0	1.282	80.0	12.9	1.65	62.7	2.88
71.0	22.0	1.562	80.0	14.9	1.84	64.9	3.26
70.5	25.0	1.763	80.0	15.7	1.98	65.8	3.58
68.0	30.5	2.074	80.0	16.3	2.02	66.6	3.90
68.0	37.4	2.543	80.0	19.5	2.43	68.1	4.38

Calculated:

% Eff.	% p.f.	Total Kva.	Armature Kva. Input.	Armature % p.f.
0	18.9	7.81	.65	92.1
20.5	22.8	8.09	.62	93.8
34.8	28.0	8.90	1.163	94.5
44.5	33.1	8.70	1.79	92.2
48.0	35.1	9.00	2.07	88.7
49.3	39.2	9.12	2.18	90.6
53.3	42.2	9.24	2.26	89.4
52.1	46.4	9.44	2.71	89.5

Run #5. Doubly-fed Static Converter. -- Showing the effect of varying the voltage impressed on the armature.

Line voltage ....80 volts.

Impressed Frequency ....25 cycles/sec.

D.C. Output.			Armature			Total Input	
Volts	Amps.	Kw.	Volts	Amps.	Kw.	Amps.	Kw.
70.0	15.0	1.050	73.0	1.9	.00	57.9	2.608
70.5	15.1	1.065	75.0	2.5	.24	58.0	2.648
72.5	15.1	1.095	80.0	8.5	1.11	62.6	2.760
75.5	16.0	1.208	85.0	18.5	2.25	65.4	2.840
80.0	15.0	1.200	90.0	28.9	3.19	75.0	2.720
84.5	15.3	1.293	95.0	44.5	4.16	82.2	3.280
90.0	15.2	1.368	97.5	58.2	5.02	89.9	3.800

Calculated:

%	%	Total	Armature	
Eff.	p.f.	Kva.	Kva.	p.f.
40.3	32.5	8.03	.24	0
40.2	33.0	8.04	.33	72.4
39.7	31.8	8.68	1.18	94.1
42.5	31.4	9.06	2.72	82.6
44.2	26.2	10.40	4.50	70.9
39.4	28.8	11.40	7.33	56.8
36.0	30.5	12.47	9.84	51.1

Run #6. Inverted Static Converter.

Frequency of supply to brush motor -- 25 cycles/sec.

Frequency of A.C. output .... 25 cycles/sec.

A.C. load in delta.

D.C. Input.			A.C. Output.			%
Volts	Amps.	Kw.	Volts	Amps.	Kw.	Eff.
10.0	25.1	.251	30.9	0	0	0
	20.5	.205	20.8	.87	.0312	15.2
	17.0	.170	15.4	1.66	.0442	26.0
	15.0	.150	12.2	2.08	.0440	29.3
	14.5	.145	11.3	2.34	.0456	31.4
	13.9	.139	9.6	2.83	.0468	33.7
	35.8	.358	0	15.10	Short-circuited	
15.0	30.0	.450	22.2	0	0	0
	22.0	.330	14.9	4.89	.1260	38.2
	19.4	.291	12.2	2.50	.0529	18.2
	18.0	.270	11.8	2.28	.0467	17.3
	11.0	.165	6.0	2.55	.0265	16.1
20.0	29.0	.580	20.5	6.54	.232	40.0

Miscellaneous Data:

The ratio of transformation between stator (primary) and the armature (secondary) of the static converter:

Frequency f	Impressed (line) Voltage	Secondary Load Amps.	Secondary (line) Voltage	Ratio of Transformation
60	109.0	0	66.5	1.640
25	84.0	0	57.5	1.460
25	88.0	8.5	60.0	1.466

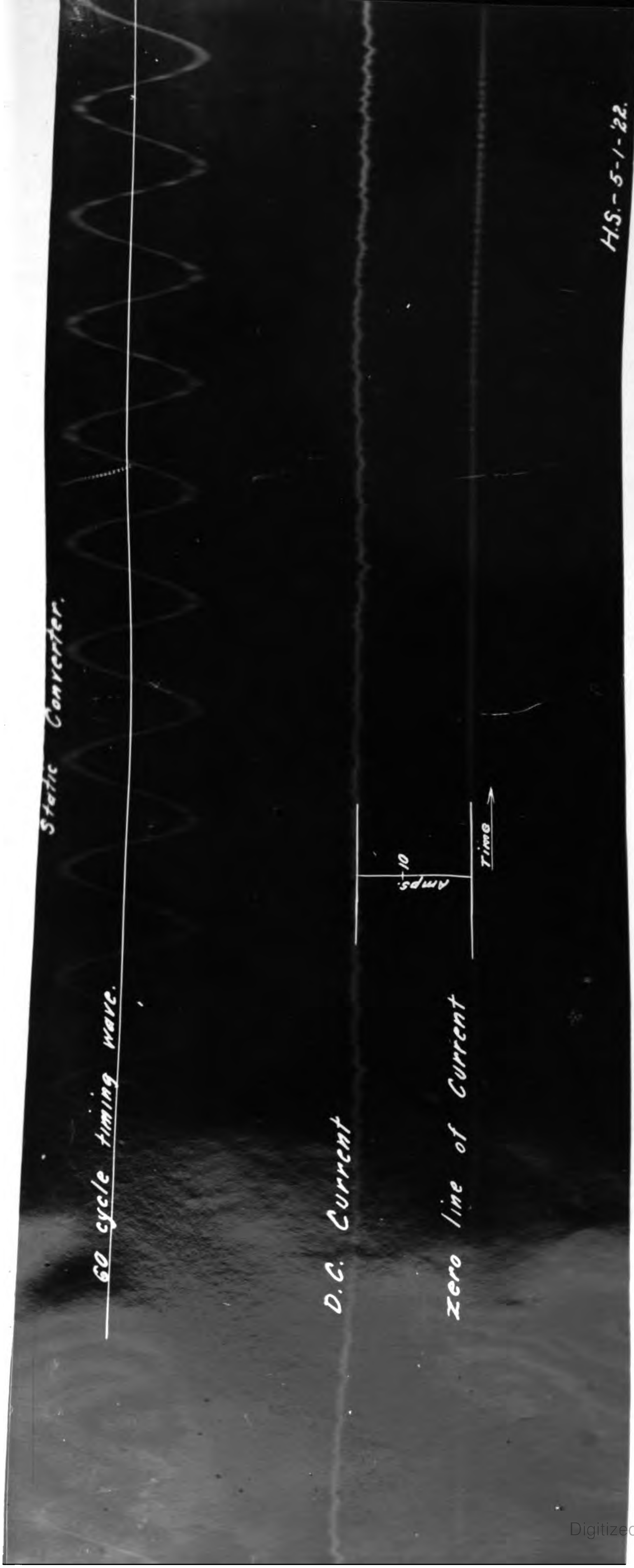
Brushes were not rotating.

Data for the Oscillogram:

D.C.Output.			A.C. Input.				%
Volts	Amperes	Kw.	Volts	Amps.	Kw.	f	Eff.
71.0	16.5	1.162	80.0	41.8	2.24	25	52.0

Power Required to Rotate Brushes:

I_1	I_2	P_1	P_2	P_t	Remarks.
Amperes		Kilowatts			
5.80	5.40	.44	.14	.58	Loaded. Voltage -- 80
3.97	3.84	.26	.03	.29	Unloaded. Frequency -25
				.29	Power to rotate brushes.


Static Converter.
H.S.-5-1-'22.
60 cycle timing wave.
D.C. Current
Zero line of Current
10
amps
Time

3. Comparison with Calculated Performance.

As a direct converter:

Conditions.			Calculated.				Experimental		
E_{ac}	I_{ac}	f	E_{dc}	I_{dc}	Eff.	Method	E_{dc}	I_{dc}	Eff.
110	25	60	100.0	25.0	65.6	a	90.0	10.5	57.5
			85.5			b			
110	25.	60	94.8	11.9	67.7	c	90.0	11.0	58.3
80	50	25	60.6	50.0	54.7	a	61.0	41.0	55.5
			109.0			b			
			77.2	39.5	55.2	c			

As an inverted converter:

Conditions.		Calculated				Experimental		
E_{dc}	I_{dc}	E_{ac}	I_{ac}	Eff.	Method	E_{ac}	I_{ac}	Eff.
20	29.0	20.7	8.84	54.6	c	20.5	6.54	40.0
10	13.5	10.4	6.42	85.6	c	9.0	3.00	34.5

The last method furnishes a good check upon the voltages. The no-load voltage checks almost exactly with the calculated value. Under load the voltage of the static converter is less than the calculated value. The calculated load currents are all higher than the experimental results. The assumption of 80% power factor introduces a large error because the unit usually operated at a much lower power factor.

The first method gives results which are in quite close agreement with the observed facts. The currents are again too large. Part of this error may be accounted for in the high resistance and irregular contact of the revolving brushes.

Only the last method was used to check the results when operating inverted. The voltages are again in close agreement, and the calculated currents are too large. The efficiency of conversion is therefore too high.

V. DISCUSSION AND CONCLUSIONS.

The tests were conducted under the disadvantageous necessity of using machines built for 60 cycle power on 25 cycle power. This accounts in a large measure for the low power-factor and low efficiency of conversion.

Fig. 7 and Fig. 8 show how the efficiency improves with higher frequency. The explanation is found in the reduced exciting currents taken by the converter. Fig.8 illustrates how the current input falls off as the frequency is raised, the load remaining approximately constant. The data shows that the direct-current voltage varies but slightly with the frequency. It has a tendency to come down because of the higher reactance.

The regulation is poor in all runs. If 3 Kw. is assumed the full-load out-put, the regulation is

$$\frac{76.5 - 61.0}{61.0} = 25.4\ \% \quad \text{when operating singly-fed,}$$

and

$$\frac{77.0 - 65.0}{65.0} = 18.5\ \% \quad \text{when doubly-fed.}$$

The regulation when doubly-fed is therefore somewhat improved. The conclusion is that the poor regulation is due mainly to the large magnetic-leakage of the stator.

The effect of putting power into the armature is shown by the characteristics Figs. 9, 10, and 11. Comparing with the characteristics of the converter when singly-fed, it will

be observed that the total ampere input becomes greater and the corresponding power-factor lower.

When the voltage on the armature is raised (Fig.11) more and more of the power is taken by the armature. The efficiency becomes a maximum when the total power input equals the armature input. This would indicate that all the alternating-current power coming in is converted into direct-current power. If the voltage is raised above this point, 89 volts, the power going into the armature is partly transferred to the stator -- the stator now acting as a secondary of a transformer -- and a circulating current is set up in the circuit consisting of the stator and armature. This is the explanation of the armature power input becoming greater than the total input from the line. The input to the stator under this condition is negative.

Fig. 11 also illustrates how the direct-current voltage could be controlled from the alternating-current side. The static converter is a fixed voltage ratio machine just as the synchronous converter.

When operated inverted, the converter could be short-circuited without getting very large currents. The machine had to be operated at an extremely low direct-current voltage because of the low resistance of the armature. The output was therefore limited. The load voltage fell off sharply at first but tended to become constant around the value of

the impressed direct-current voltage. The conclusion is that the experimental machine is not suitable for inverted operation.

From these tests one would conclude that the static converter could never compete with the synchronous converter because of the low power-factor and low efficiency of conversion. It should be pointed out again, however, that the test conditions were not conducive to getting either high efficiency or high power factor. If a static converter were built like a transformer, without an air gap , placed in insulating oil and a serviceable commutating mechanism designed, the output could be enormously increased. The elimination of the air-gap and the use of a good magnetic circuit would raise the power factor. Such a machine might well be used in the future where the synchronous converter is found today. It has the advantage of having no heavy rotating parts, is independent of direct-current for excitation, and seems to commutate under all loads without the slightest sparking.

VI. BIBLIOGRAPHY.

1. Cairns, C.F. -- The Cabot Converter -- Proc. Inst. Radio Engrs. Vol. 7, No.3, June 1919. Page 281-291.

2. Colles, G.W. -- History of Rotary Transformers -- Journal Franklin Institute. Serial commencing Mar. 1901.

3. Electric Ry. and W. Elec'n, Jan. 27, 1907. Pages 70 -170.

4. Hutin and Leblanc -- Patent #644553, Feb.27, 1900. Apparatus for Converting Alternating into Continuous Currents, and Vice Versa. Filed June 19, 1899.

5. Kimball and Barr -- Elements of Machine Design -- N.Y. 1909.

6. Koch, F.J. -- Electrotech Zeitschr. Oct. 10, 1901.

7. Lawrence, R.R. -- Principles of Alternating Current Machinery -- N.Y. 1916.

8. Machinery Handbook -- Industrial Press, N.Y. 1919.

9. Merriman, M. -- Mechanics of Materials -- 11th Ed. N.Y. 1916. Page 424.

10. Pollak Rectifier. -- Electrical Engineer, Vol.16, N.Y. Page 238.

11. Standard Handbook for Electrical Engr. N.Y. 1915.

12. Sterzel, K. -- Electrotech Zeitschrift -- Oct.3,1903.

13. Thompson, S.P.--Report on Motor Generators, Converters and Rectifiers -- International Electrical Congress, Turin. Electrician (London) Sept. 29, 1911.

14. Thompson, S.P. -- Dynamo Electric Machinery --4th Edition, page 652.

APPROVAL.

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in amanner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

John P. Price
Name
Assoc. Prof. of Elec. Engr.
Title